NASA Technical Memorandum 4637

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Summary

This paper describes the techniques developed for measuring stagnation-point radiation in NASA's canceled Aeroassist Flight Experiment (AFE). It specifies the need for such a measurement, the types and requirements for the needed instruments, the Radiative Heating Experiment (RHE) developed for the AFE, the requirements, design parameters, and performance of the window developed for the RHE, the procedures and summary of the technique, and results of the arc-jet wind tunnel experiment conducted to demonstrate the overall concept. Subjects emphasized are the commercial implications of the knowledge to be gained by this experiment in connection with the Aeroassisted Space Transfer Vehicle (ASTV), the nonequilibrium nature of the radiation, concerns over the contribution of vacuum-ultraviolet radiation to the overall radiation, and the limit on the flight environment of the vehicle imposed by the limitations on the window material. Results show that a technique exists with which the stagnation-point radiation can be measured in flight in an environment of interest to commercial ASTV applications.

Nomenclature

T_e	electron temperature
T_{eq}	equilibrium temperature
T_r	rotational temperature
T_t	translational temperature
T_v	vibrational temperature
t	time

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Acronyms

AFE	aeroassist flight experiment
ARC	Ames Research Center
ASTV	aeroassisted space transfer vehicle
BH-1	Birge-Hopfield system of molecular nitrogen
CDR	critical design review
GEO	geosynchronous Earth orbit
IR	infrared
L/D	lift/drag ratio
LEO	low Earth orbit
PAET	planetary atmospheric entry test
RCS	reaction control system
RHE	radiative heating experiment
STS	space transport system
UV	ultraviolet
UV-VIS	ultraviolet-visible
VUV	vacuum ultraviolet

I. Introduction

Large vehicles entering the Earth's or a planetary atmosphere will experience surface heating as they are enveloped in a region of shock heated gases. The design of the thermal protective system must be based on predictions of this heating if the vehicle is to be efficient (e.g., as light as possible) or even survive. At low velocities convective heating only is usually of consideration. However at planetary entry speeds, typically above a few kilometers per second, extremely high temperatures are developed in the stagnation region gases, and these gases can radiate intensely. Depending on the vehicle size, the heating from this radiation can be important and it must be the considered in the heat shield design. A new class of space transfer vehicles, employing aeroassist, will require protection from this heating.

Accurate radiative heating predictions will be required to assure that the vehicle is not overly burdened by thermal protection conservatism.

The eventual introduction of a permanent space station will usher in a new capability for planetary exploration and utilization of Earth/moon space. Lunar and planetary mission vehicles could be assembled, deployed, and retrieved on this platform without ever returning to Earth. New, efficient, space transportation systems are needed to exploit this capability. A promising technique is aero-assist, which refers to flying the vehicle into the Earth's upper atmosphere and using aerodynamic forces to slow the vehicle and redirect it into a desired orbit in contrast to relying on retrorockets for orbit modifications. An Aeroassisted Space Transportation Vehicle (ASTV) is equipped with a large, lightweight, low lift/drag (L/D), forebody heatshield. Returning from a mission, an ASTV would decelerate and alter its orbital parameters for rendezvous with the space station by flying through the upper atmospheric (fig. 1) and direct the forebody aerodynamic forces by controlling pitch and roll. After the ASTV exits the atmosphere in the desired orbit and links with the station, the space transport system (STS) could then provide the link with Earth.

Lightweight, efficient heat shields are necessary to take advantage of aeroassist. The requirements for decelerating retrorockets and their fuel would be reduced or eliminated if such heat shields could be designed and built. Potential exists for substantially lower mass associated with a space transportation mission, and this potential translates directly to lower mission cost.

The present capability to predict ASTV heat shield requirements is based on the existing capabilities to accurately model aerothermodynamic processes. These models, based on many approximations, need validation data to reduce uncertainties, especially for predictions of the heat load from the shock layer radiation. The uncertainties in these methods need to be reduced substantially before optimum heat shields can be designed with minimum conservatism so the benefits aren't degraded by excessive conservatism.

A NASA Aerocapture Technology Working Group was formed in 1980 to address this challenge. This group identified specific technical issues that must be addressed to develop the design capability for routine use of aero-assist to modify orbits. The group agreed that an adequate technical data base does not exist at this time and that the best and perhaps only way to develop one was from a

Figure 1. Artist's depiction of the AFE spacecraft maneuvering through the Earth's upper atmosphere.

properly designed flight experiment. This data base would be used to improve and validate computational models that would form the basis for ASTV design codes.

A flight vehicle was defined: The Aeroassist Flight Experiment (AFE) (ref. 1) vehicle would be instrumented to gather, in situ, flight data. Radiative heating was identified as a critical heating source to be understood, and the Radiative Heating Experiment (RHE) (ref. 2) was identified to help answer the radiation questions.

The proposed AFE vehicle is depicted in figure 2. It was to be deployed from the STS into low Earth orbit (LEO). Rockets would then accelerate it to a velocity and altitude representative of an ASTV returning from geosynchronous earth orbit (GEO). The AFE would perform an aeropass, exit, and return to the STS for recovery.

The flight regime of a maneuvering ASTV is compared with those of the STS and the Apollo in figure 3. The ASTV entry is initially similar to the Apollo entry since both would be returning from relatively distant missions (GEO or lunar). But the ASTV is maneuvered away to decelerate and change its orbital parameters, mainly between 75 and 90 km. Then it leaves the atmosphere in an orbit accessible to the STS. Although the STS and Apollo trajectories pass through the ASTV maneuvering altitude, neither substantially alters its velocity there.

The AFE configuration, given in figure 2, is shaped like an operational ASTV but at one-quarter scale. The diameter, limited to the dimensions of the STS cargo bay, was 4.26 meters. The vehicle was designed to fly at a constant trim angle of 17 degrees, to produce drag and lift, and to fly a trajectory of an ASTV maneuvering from GEO to LEO. The planned trajectory is shown in figure 4. The atmospheric entry velocity is 9.89 km/sec at 122 km altitude. Navigation control was to be by rolling the spacecraft to redirect the L/D vector. The orbit engineers optimized the flight profile to achieve a data acquisition period with a radiating, nonequilibrated shock region separated by an equilibrated region from the boundary layer and at conditions of important heating to an ASTV. The trajectory from entry to exit would take about 600 sec. Details of the AFE flight are found in reference 3.

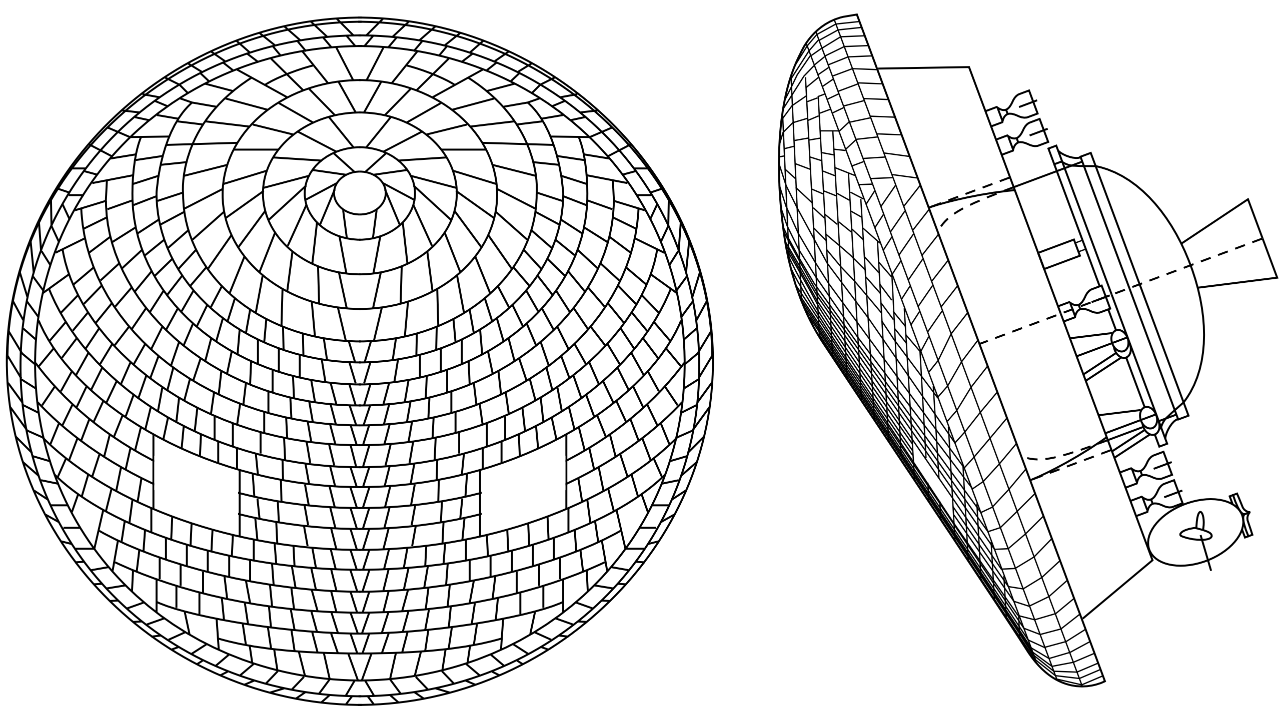

Figure 2. The proposed AFE spacecraft. The thermal protection tiles are indicated on the forebody. The main thruster rocket and reaction control system (RCS) are shown on the base. The direction of the force vector with respect to the velocity vector was to be controlled by roll.

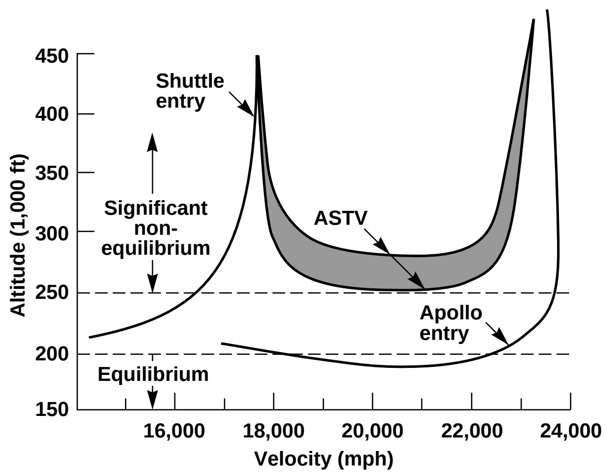

Figure 3. Flight regimes of returning STS, Apollo, and ASTV maneuvering from high Earth orbit (geosynchronous or lunar) to LEO for rendezvous with a space station or STS.

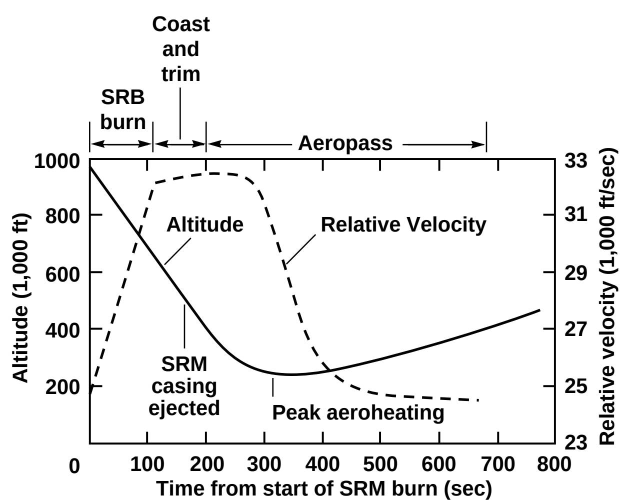

Figure 4. Predicted flight profile of the AFE spacecraft. The main rocket is fired at about 300 km and is ejected after about 160 seconds (sec). The entry velocity of a returning spacecraft from GEO is achieved at about 100 sec after ignition. Most of the deceleration is achieved at about 60 km from 280 to about 400 sec.

The goals and engineered design of the RHE were well matured and many of the design challenges were successfully met before the AFE was canceled. Experiment objectives and flight instrument requirements were also developed. One required development was a window that would withstand the harsh flight environment and the aeropass heating pulse and transmit the required spectral radiation information from the shock layer to the detector. Several window concepts were examined and viable designs were tested. The results of these efforts should have application elsewhere.

The purpose of this paper is to present the RHE science objectives, the required RHE instrument design performance, and the resulting RHE instrument design including the window.

II. Experiment Science Objectives

Background

Distinguished from other spacecraft by the incorporation of a large, blunt, aerobrake surface, an ASTV would meet the atmosphere head-on at hypersonic speed and be exposed to substantial surface heating. This heating would include a radiative component perhaps equal to the convective heating. Accurate predictions of this heating requires the solution of the real gas conditions of the flow-field environment of the vehicle. Predictive codes, incorporating realistic gas properties, are being developed at Ames and elsewhere. Predictions of the AFE shock layer properties, from an Ames Research Center (ARC) two-temperature aerothermodynamic code, are shown in figure 5 from reference 4. The calculation is for the conditions of peak heating (9.5 km/sec and 77 km altitude). The vehicle size, velocity, and altitude result in a shock layer predicted to be composed largely of thermally nonequilibrated gas. This phenomenon is evidenced by the large difference between the high translational temperature, T_t, and the vibrational temperature, T_v, near the shock. This difference diminishes toward the surface to a more nearly equilibrated state. The initial collisions that form the shock convert the kinetic energy of the impact velocity of the air directly into random motion, which is T_t. Directly behind

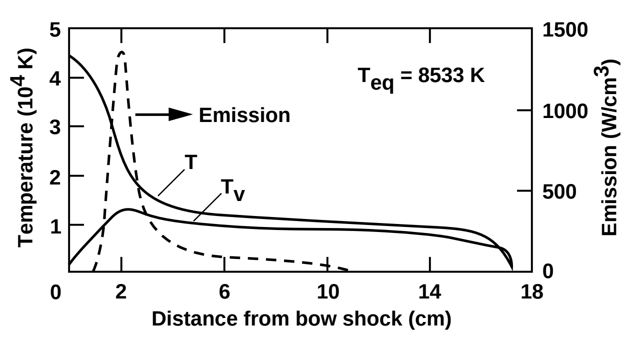

Figure 5. Calculated AFE stagnation region kinetic and vibrational temperature and local radiation. The local values are shown as a function of distance from the bow shock. The shock thickness is about 18 cm, and nearly one-third out of equilibrated.

the shock, T_t is very high, about 50,000 K. Subsequent collisions and other kinetic processes distribute this energy into other internal modes. N_2^+ is formed, N_2 and O_2 dissociate, and reactions proceed to produce NO. The vibrational levels of the molecules eventually are populated and T_v is seen to approach the decreasing T_t. The temperatures relax toward each other to about 8500 K as the gas equilibrates. At the low densities of a maneuvering ASTV this relaxation process occupies a significant portion of the shock layer.

An important objective of the AFE was to generate a data base to validate predictive models of radiative heating at the ASTV forebody stagnation region. As seen in figure 5 this heating is predicted to be dominated by emission from the nonequilibrated gases near the shock. The thickness of this region is determined, approximately, by the collisions that drive the gas kinetic processes. For the same maneuver this thickness (and therefore the radiative flux from the nonequilibrated regions) is approximately constant with vehicle size (ref. 5). This zone merges with the cooler boundary layer on small configurations at high altitude conditions (ref. 6). This is the case with models that could be used in ground based tests (ballistic ranges, shock tubes, or arc-jet wind tunnels), namely models of sizes much less than one meter. Validating data from these kinds of tests would be hampered by a distorted relationship between important kinetic processes as compared with a full-scale ASTV. In addition, modeling the shock layer of these small shapes would necessitate solving the merged boundary layer with the incorporation of a different boundary condition from the full-scale case. Extrapolation from ground based test results to full-scale conditions would involve many uncertainties and require large conservatism. Further, some three-dimensional (3-D) calculations have indicated chemical processes with relaxation times on the order of the AFE shock layer residence time. Phenomena of this class would never be observed on a small test configuration. In contrast, the shock layer of full-scale vehicles flying at low altitudes (high densities) will consist mainly of equilibrated gases with a very thin, nonequilibrated region at the shock. The STS experiences most of its heating under this condition, as did the Apollo. An instrumented subscale ASTV, such as the AFE, flying an ASTV maneuver, was needed to meet the technical requirements. The AFE diameter of 4.26 meters would be adequate to provide an isolating zone of nearly equilibrated gas between the nonequilibrated region of the shock layer and the cooler boundary layer and would provide a suitable platform to develop the data base to help resolve the radiative heating and other ASTV design issues.

Shock Layer Radiation

The radiating shock region contains a mixture of gas species over a large range of conditions and involves many kinetically limited processes (ref. 7). The surface flux, even though spectrally resolved, would contain emissions from a complicated source. Surface flux measurements of molecular band systems, for example, would be the aggregate emissions, along lines-of-sight, from the populations of excited molecules over a range of thermodynamic and molecular conditions. Although apparent temperatures (kinetic, rotational, and vibrational) would be indicated in the data, they would, in reality, be the summation of a variety of concentrations and conditions and might include absorption. Analysis of these data to understand the conditions within the shock layer would require companion computational models to correlate the measurements with a realistic representation of the physical principles of coupled high speed flight and radiation (spectroscopy). This correlating model would be, of course, an important step toward a validated ATSV design code.

Preliminary codes describing the radiating shock layer of an ASTV have been developed at ARC. These codes were the basis for developing the science objectives for the RHE. Predictions of the radiant flux onto the surface of the maneuvering AFE were done for species that were expected to be important. Figure 6 is the calculated spectrum of the radiative flux onto the surface of the AFE near peak heating under the assumption of an optically thin shock (ref. 4). Molecular systems as well as atomic lines are evident. Atomic nitrogen and oxygen lines are seen in the vacuum ultraviolet (VUV) (100 to 180 nm), with the Birge-Hopfield system (BH-1) of molecular nitrogen as the underlying background. Molecular bands from nitric oxide[1] are seen from 190 to 300 nm. Molecular nitrogen[2] systems contribute energy from 280 nm on and then merge with other, stronger molecular band systems,[3] which then dominate the molecular radiation from 300 nm to the infrared (IR). Atomic lines are also seen in the IR. Very little radiative heating is expected from the IR beyond one micron.

Because of the subscale size of the AFE, radiative heating is predicted to represent only about 10% of the total heating and therefore is not of overwhelming concern to the AFE. The RHE was not configured to assess the radiative heating, qua heating, to the AFE, but rather to gather a radiative flux data base to identify the important

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[1] NO_γ, $A\,^2\Sigma^+ \rightarrow X\,^2\Pi$, and NO_β, $B\,^2\Pi \rightarrow X\,^2\Pi$.
[2] $N_2(2+)$ bands, $C^3\Pi_u \rightarrow B^3\Pi_g$.
[3] $N_2^+(1-)$, $B\,^2\Sigma_u^+ \rightarrow X\,^2\Sigma_g^+$, CN_v, $B\,^2\Sigma^+ \rightarrow X\,^2\Sigma^+$, and $N_2(1+)$, $B^3\Pi_g \rightarrow A^3\Sigma_u^+$.

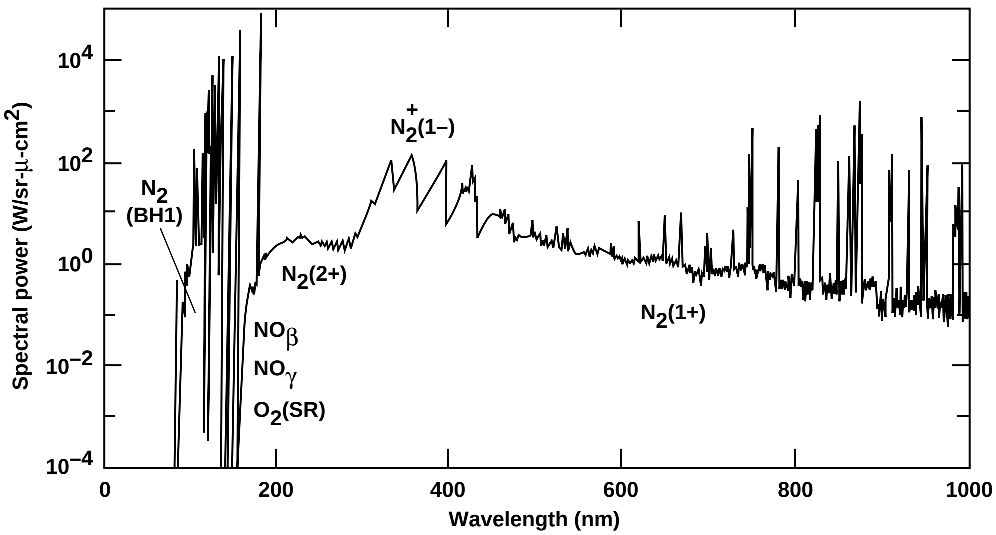

Figure 6. Prediction of the important radiation flux onto the surface of the AFE near aeropass peak heating. The intense atomic lines in the VUV are indicated below 200 nm.

radiators and to validate the calculated gas properties of the flow field calculations including radiative transport. Such a validated model could then be used to establish the requirements for an efficient full-scale ASTV heat shield.

Vacuum ultraviolet– Some of the atomic lines in the VUV are extremely intense and therefore are of concern. Various models of these line emissions predict widely different radiative heating levels ranging from insignificant amounts to levels dominating the overall heating (refs. 4, 8, and 9). Since the VUV emissions are from transitions to the ground states, a description of the surface flux is complicated by spectral absorption from a range of conditions of the absorbers between the emitters and the surface. A realistic, predictive model must include accurate details of the absorption and emission.

Calculations done at ARC (ref. 4) indicate that if the VUV line radiation were to reach the surface unabsorbed, the resulting radiative heating would be vastly more than the convective heating. The VUV emission is from the nonequilibrated regions close to the shock. Here the spectral lines are strongly Doppler-broadened by the high kinetic temperature. The cooler parts of the shock and boundary layer are calculated to absorb these strong features directed toward the surface. These cooler absorption regions have spectrally narrower absorption features resulting in the curious effect that the intense region at the line center is absorbed and only the energy in the wings reaches the surface with any heating significance. The local, total line emission can be calculated precisely, but the ultimate energy reaching the surface can be strongly affected through absorption by the intervening shock and boundary layer gases. Calculations of the total radiative transfer to the surface require accurate knowledge of the spectral distributions of energy over the emission and absorption line shapes. The ARC model predicts that absorption will reduce the VUV flux by 99.8% to represent about 25% of the radiative heating of the AFE, but errors in the calculated line shapes could result in disproportionate errors in the prediction of surface heating rates.

ARC predictions (ref. 4) of the total flux from all the VUV atomic lines over the AFE trajectory are plotted in figure 7 together with predictions of the total radiative surface flux and the flux from the group of 174-nm atomic nitrogen lines. The predictions at the low densities ($0 < t < 60$ sec, and $t > 250$ sec) where the intensities are low are not accurate and are represented herein only as qualitative. The total radiation from the VUV lines is predicted to be controlled by self absorption, and it becomes optically thick throughout the period of significant radiant heating. The importance, and perhaps spectral details, of the heating from these intense VUV lines needs to be ascertained. The lines at 174 nm contribute substantially to the total VUV and they too become optically thick. It is important to characterize the transition from low to high optical density. Therefore, measurements of these lines during the early portion of the aeropass, and thence until they become optically thick, is necessary. Also important, but secondarily, would be the analogous measurements on the outward leg of the trajectory to establish the transition from optically thick conditions to as far as the intensity would permit measurements. These measurement periods are predicted

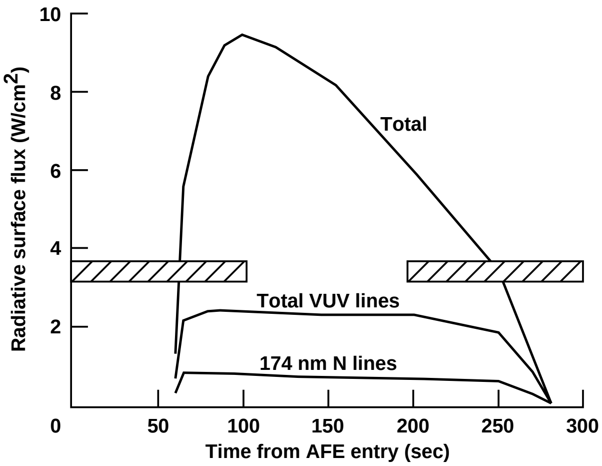

Figure 7. Prediction of the surface intensity of the 174-nm atomic nitrogen lines, the total of all VUV lines, and the overall radiative surface flux over the AFE trajectory. The regions important to achieve the VUV data are indicated by the hatched areas.

to be from entry to 100 sec, and from 200 sec to exit, and they are indicated in figure 7 by the hashed bars.

Ultraviolet-visible (UV-VIS)– Most of the heating of a maneuvering ASTV is predicted to come from the strong N_2^+(1–) and CN_V molecular band systems in the near UV and visible regions of the spectrum. From the viewpoint of heating this spectral region is probably optically thin. Measurements of the detailed spectral radiative flux in this region would help identify unexpected, but important, radiators in the shock layer and would be the basis to validate predictions of the conditions of these gases. Code validation of these measured molecular spectral features would be a very powerful demonstration of the predictive capabilities.

Infrared– Rich and diagnostically important atomic line radiation is predicted from oxygen and nitrogen in the infrared. These lines also emanate from the hot regions near the shock. The intensities of these lines range from weak (unabsorbed) to moderate (partially absorbed) levels. Measurements of the unabsorbed lines would yield information, unmodified by absorption, about the emission phenomena from the gas near the shock. Measurements of the flux from the partially absorbed lines would yield information about the absorption properties of the intermediate, cooler gases.

Under the conditions of a maneuvering ASTV, electronic excitation of these atoms is by electron collisions. Measurements of the IR line intensities would help validate predictions of ionization levels and electron gas temperatures. The absolute measurements of the intensities of these lines could also help determine the atomic density profiles through the shock.

III. RHE Instrument Performance

The objective of the AFE was to gather flight data to help develop the design technologies needed for efficient ASTVs, and the RHE objective was to provide data to address the radiation issues. Since the radiating medium was complex in composition and state, surface flux measurements alone would not be useful. The RHE relied on companion predictive codes both to develop the objectives and to interpret post flight data. This experiment/code relationship concept was successfully employed in a pioneering flight experiment, the planetary atmospheric entry test (PAET) (ref. 10). PAET was an Earth entry experiment, which measured shock layer radiation with nine spectrally resolved radiometers. The data were combined with results from a computational model to determine properties of the ambient gas. This test was designed to demonstrate the potential use of data obtained during the high speed entry of a planetary probe to determine the atmospheric composition.

Successful predictions of the observed RHE quantities by the physics of the gas chemistry and spectroscopy incorporated in the computational codes would require matching many observed quantities. Consistency of the results would in turn result in confidence in the predictions of the details of shock layer gas conditions. The RHE was to make absolute spectral measurements of the stagnation region surface flux, under conditions of important radiative ASTV heating, to validate the VUV- and longer-wavelength radiation calculations, and to help determine the shock layer gas conditions (concentrations, T_t, T_v, rotational temperature (T_r), and electron temperature (T_e)). In each case measurements would be made at several locations through windowed penetrations of the AFE heat shield at the stagnation region.

These objectives, with predictions of the surface radiative flux (see figs. 5–7), formed the basis for the RHE instrument performance requirements. The requirements were, in part, as follows:

1. Obtain spectrally resolved surface flux data from the AFE stagnation region gas cap at several locations on the heat shield. Measure the flux from the atomic nitrogen lines at 174 nm to provide assessment of the VUV calculations. Measure the range from 200 to 900 nm with sufficient spectral resolution for code validation.

2. Obtain spectrally integrated data by using a wide band detector, such as a blackened thermopile, to measure the spectral radiation from the VUV to the IR. These data

would provide a level of redundancy with the spectral instrument and would help determine the sufficiency of the spectral data to provide validation for overall radiative heating.

3. Provide a windowed aperture to isolate the detector from the shock layer gases. The window is to be mounted flush with the spacecraft surface so as to not disturb the boundary layer flow.

4. Obtain a broadband measurement and a complete spectrum every 3 sec during the 600-sec AFE trajectory.

These requirements formed the basis for a Request for Proposal and a fully competed contract was awarded to Martin Marrietta Astronautics Group (MMAG), Denver, CO, for design and construction of the flight instruments.

IV. RHE Instruments

The contractor developed the design of the instruments and completed a Critical Design Review (CDR) for all but the windowed aperture. The final design, described in detail in reference 11, is summarized below.

MMAG determined that instrument requirements could be met using a small, grating spectrograph (0.125 meter focal length) with a scanning, linear photocathode array detector. The UV spectral sensitivity of a sample, windowless, commercially available array detector was measured to extend to below 160 nm by the MMAG team.[4] Their measurement result is shown in figure 8. Spectral resolution of 0.6 nm from 174 to 800 nm was attainable. Sensitivity measurements, together with predictions of the radiation intensities, showed that this setup was adequate to meet the scientific objectives, including intensity measurements of the 174-nm atomic nitrogen lines.

Sensitivity and dynamic range requirements for the spectrally integrated data were met with a thermopile detector. The spectral response of such a detector, for purposes herein, would be limited only by the window transmission.

Flight Window Design

The window design was not matured to a CDR level at the time of program termination. Although a flight article had not been designed and tested, considerable progress had been made. Viable designs, which would survive the aeropass and meet all, or part, of the experiment objectives, had been developed and tested. The results indicated window configurations that have a high likelihood of flight worthiness. These designs and their expected science return are described below.

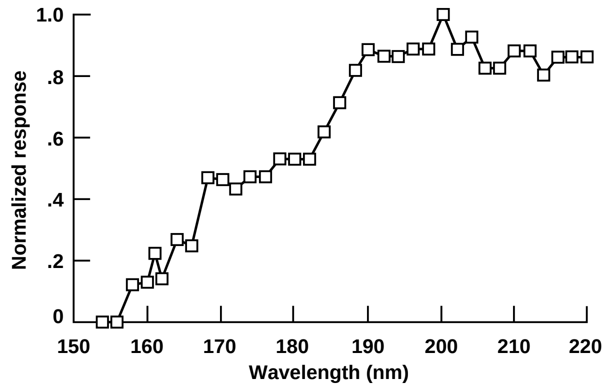

Figure 8. Vacuum UV response of the linear detector measured by MMAG, Denver, CO, team.

Requirements– Window design requirements included adequate optical performance to meet the scientific objectives and survivability without compromising mission safety. The scientific objectives required, in part, that the window transmit radiation over the range of interest, e.g., from 174 nm to several microns, over important portions of the trajectory. The window and its mounting would experience high convective heating rates that might include heat liberated from catalytic reaction of recombining atoms diffusing to the surface and thermal shocks.

Sapphire was determined to be the material of choice for the window (ref. 12).

Spectral transmission– At room temperature, sapphire transmits UV radiation from well below 174 nm to well into the IR. The short wavelength cutoff of sapphire's transmission is due to the long wavelength edge of a broad absorption band. But at elevated temperatures this absorption band widens and extends to longer wavelengths. Thus the useful VUV transmittance of a sapphire window changes with temperature—high window temperatures degrade the short wavelength transmission region. A discussion of this phenomenon, from the standpoint of glasses, is in reference 13. The maximum sapphire window temperature that would be useful for measurements at 174 nm was measured at ARC to be about 800°C (1472°F) and is discussed in reference 12. It was done by measuring the 174-nm transmission of a heated specimen window as a function of temperature. The results are shown in figure 9.

[4]Laura Wood-DeFoe, Steve Coda, and Deborah Lowrance, MMAG, private communication.

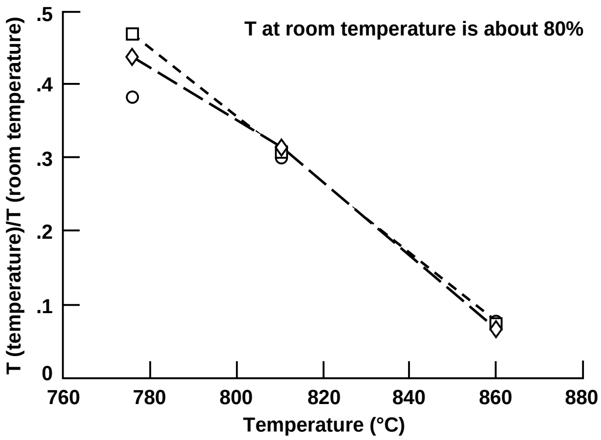

Figure 9. Sapphire transmission at 174 nm as a function of temperature. The transmission at elevated temperatures is shown rationed to the value at room temperature.

The short wavelength cutoff of sapphire IR transmission, about 5 microns, insures that the aeropass heating will not degrade the optical transmission at the IR wavelengths of interest herein (e.g., 2 microns).

Window heating– The AFE aeropass heating rate is shown in figure 10. This heating pulse would rapidly raise an uncooled window to temperatures well above 800°C. Because of sapphire's low IR emissivity radiative cooling does not significantly help maintain the desired temperature. To achieve the required UV performance the entry heating would have to be offset by a thermal mass to maintain a manageable temperature.

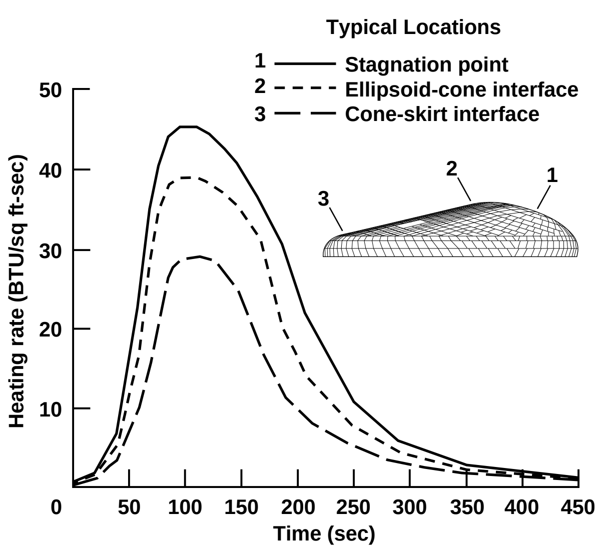

Figure 10. Calculated aeropass heating rates for the AFE at three body locations.

The minimum design requirement that could meet the science objectives is that the window maximum temperature not exceed 800°C for at least the first 100 sec of the entry, and then, if possible, again during the period after 200 sec; the desired goal would be to maintain the temperature below 800°C for the entire aeropass.

Window designs– A development program was conducted and many design concepts were built and subjected to laboratory tests. These tests consisted of exposing the windows and their mounting configurations to various heating loads simulating the AFE entry heating and included aggressive, overly conservative testing in an arc-jet wind tunnel (ref. 12). Successfully surviving these tests would insure that the design would survive the aeropass and not pose a risk to spacecraft or the experiment. Some of the test specimens were instrumented with thermocouples to develop computational models of the in-depth thermal response of the window and its mount during the arc-jet tests.[5] These models were in turn used to predict the thermal response during the flight mission.

Two design concepts used in the arc-jet wind tunnel tests, one "uncooled" and one "cooled," were shown to be promising as bases for design of a flight window that would survive the AFE entry environment and yield scientific data. Both designs used niobium in the construction of the mounting hardware. The regions of the niobium that could be exposed to the shock heated air were coated with a silicide coating to protect them from chemical erosion.[6]

The uncooled design employed alumina paper and fibrous insulation (FRCI-15, STS type heat shield material) to reduce the thermal conductance between the sapphire and its mount (fig. 11). This design was instrumented and tested in the arc-jet wind tunnel. Windows of 13.7-mm diameter with thicknesses from 4 to 12 mm were not damaged during the arc-jet tests.

Predictions of the in-flight thermal performance of the uncooled design during the AFE aeropass are shown in figure 12. This window would be adequate to gather data in the UV-VIS and IR spectral regions over the entire trajectory. The hottest portion of the window is predicted to reach 800°C at about 130 sec into the trajectory. Thus measurements could be made of the 174-nm region for the initial portion of the trajectory but the window would be too hot after 200 sec.

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[5] A. Stewart and Thomas Squire to James O. Arnold, RTM:234-1, Sept. 1992, private communication.
[6] Louis Salerno, NASA Ames Research Center, private communication.

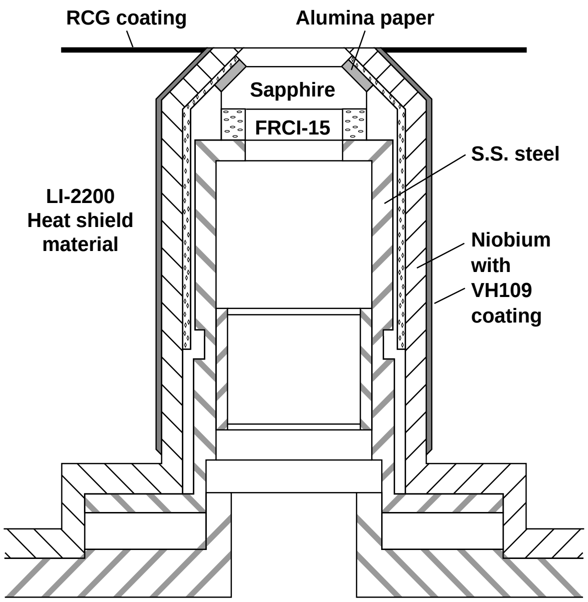

Figure 11. Sketch of thermally isolated sapphire window assembly.

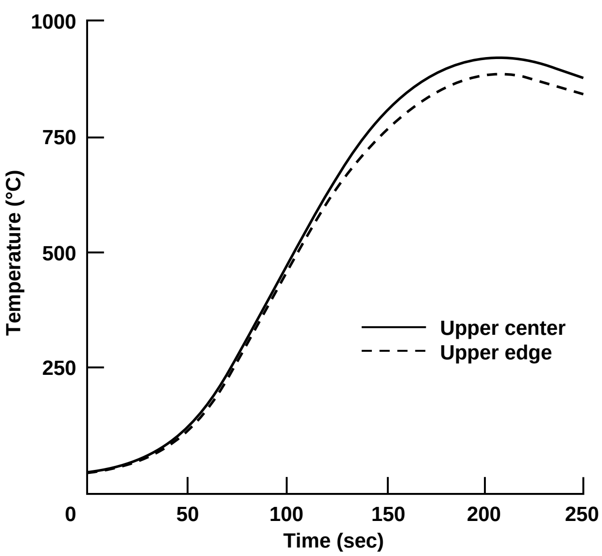

Figure 12. Predicted temperatures of thermally isolated sapphire window during AFE aeropass. The center of the window reaches 800°C at about 130 sec into the trajectory. This window would be capable of providing reliable 174-nm data for the initial portion of the aeropass, but would be too hot for the later, returning portion of the mission.

Two versions of cooled designs were evolved by the instrument contractor, MMAG. Both of these windows were cooled by conduction through a copper element to the metallic mounting and thence to a heat sink. High thermal conductivity was assured by a copper element that was brazed with a eutectic bond to the inner surface of the sapphire and in turn was brazed to the upper end of the support tube (ref. 12). The procedure for the eutectic bonding was developed by MMAG as part of the contract. One version employed a 14.5-mm-diameter window with a copper screen, 50% open, bonded to the surface as the copper element. The other version employed a 10.7-mm-diameter window without a screen but with a copper washer bonded to the flat edge of the window. Both of these configurations were built and neither was damaged during the arc-jet tests. Both designs would transmit the same amount of radiation and would satisfy aperture requirements of the experiment. As will be discussed, the smaller window needs to be a negative lens to meet the AFE requirements for solar calibrations. The cooled configurations are shown in figure 13.

Predictions of the performance of the cooled designs in the configuration of the test specimens were not made. Instead a recommended cooled design, as yet untested, was developed based on test results and computations described in reference 14. This design is shown in figure 14. Note that this design shields the silicide coated areas of the holder by overlapping with the heat shield material. This overlapping would reduce the problem of possible window contamination from the coating. Predictions of the thermal performance of this design during the AFE aeropass are shown in figure 15. The maximum temperature of this window remains below 800°C for the entire aeropass so this window would meet the thermal goal. The scientific objectives could be met over the entire aeropass.

Solar Calibrations

In order that the RHE data be useful, it must be credible. Experience with absolute measurements of radiation teaches the value of calibrating before and after a measurement. But the RHE instrumentation would not be available for laboratory testing for a substantial period before the flight, perhaps as long as one year, and for a substantial period after the flight. The sun would provide a useful calibration source that would be available just before and just after the aeropass: The source strength can be well characterized, and there is no problem with atmospheric interference. The UV-VIS to IR spectral region would be well calibrated, but scattered light problems within the spectrograph would make calibration

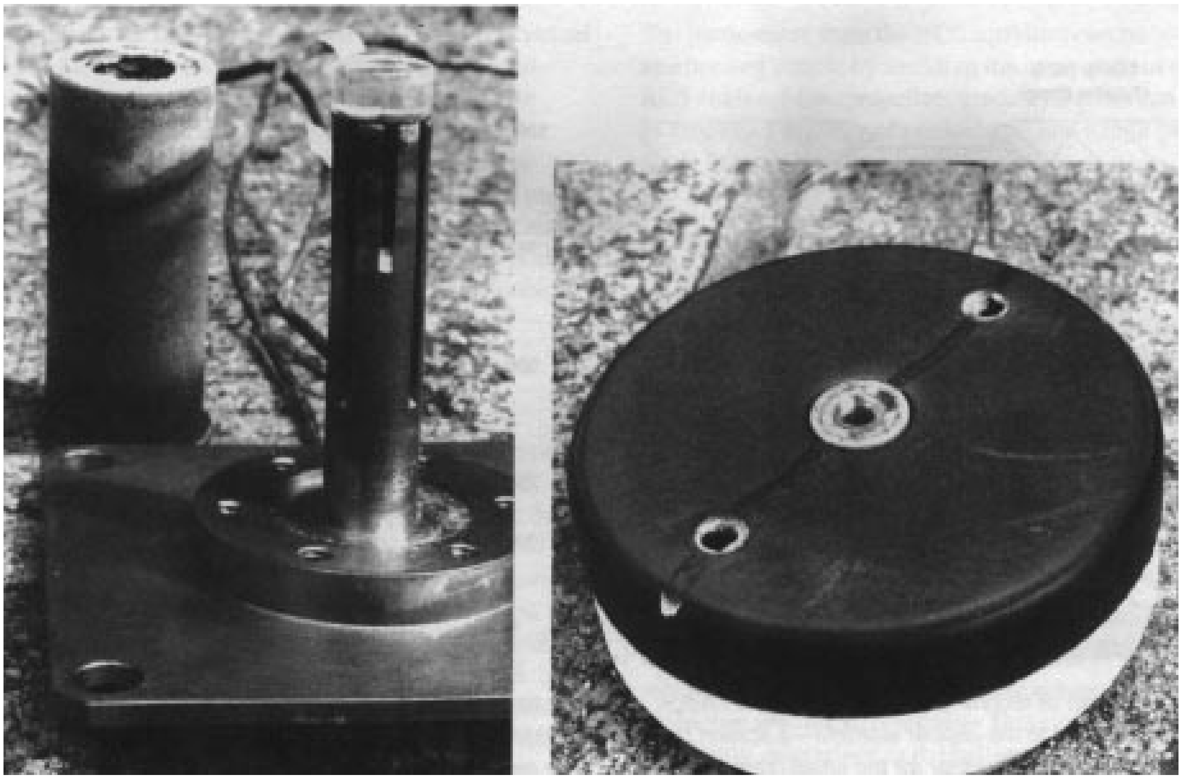

Figure 13. Left: test specimen of MMAG's smaller cooled sapphire radiometer window design. The window in the foreground is 10.7-mm diameter and is brazed on the edge to a copper washer which is, in turn, brazed to the mount to provide a heat sink. In the background is the outer niobium tube with its silicide coating. This specimen had successfully survived arc-jet tests, hence the discoloration from heating. Right: window assembly mounted in the test model that was used in the arc-jet tests. It is constructed of STS-type heat shield material with a ceramic coating. The flow was perpendicular to the flat face. The two small holes contained calorimeters used during the testing. The portion of the window exposed to the flow is shown in this view.

at 174 nm difficult. A spectrally selective filter would probably be required during this calibration.

Calibrations using the sun were deemed to be important to ensure data credibility. However, these calibrations required spacecraft resources to be expended to point each radiometer in turn at the sun. In addition, the radiometer viewfield needed to be adequate to accommodate errors in navigation, pointing accuracy, and spacecraft drift during the calibration time. In the AFE case, a circular, radiometer viewfield of 22 millisteradians was required to guarantee capture of the entire sun's disc without vignetting. The radiometer mounting requirements behind the heat shield dictated a window diameter of 14.7 mm to achieve this viewfield. The arc-jet tests suggested that an uncooled window this size would suffice at the cost of the later period VUV data. The larger cooled window required a screen brazed over the entire under surface of the sapphire, the presence of which would make it difficult (or impossible) to guarantee what fraction of the sun was obscured by the opaque portion of the screen.

The maximum viewfield, determined by the window diameter (based on performance requirements) with the minimum distance from the window to the instrument aperture (based on spacecraft requirements), will not subtend an adequate viewfield for solar calibration needs. The viewfield of the small, edge cooled window could be increased without compromising the radiometer objectives by fashioning the inner surface of the sapphire into a negative lens. The effect would be to increase the viewfield for solar calibration purposes without decreasing the sensitivity with respect to the shock layer radiation from that of the flat cooled windows. With respect to the radiometer, the radiating shock layer is a relatively uniform, extended source, but the sun is a point source. Such a lens would slightly alter the region of the shock being measured but would not change the shock layer flux reaching the radiometer. An illustrative design of a lens-apertured window, based on the dimensional

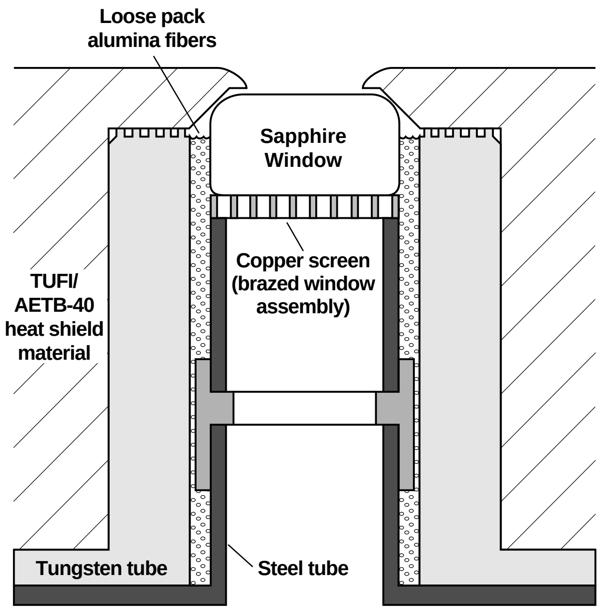

Figure 14. Sketch of recommended RHE window design. Heat is transmitted to the copper element—a screen for the large diameter or a washer for the small diameter. The window holder is shielded from the shock region gases by overlapping with the heat shield material.

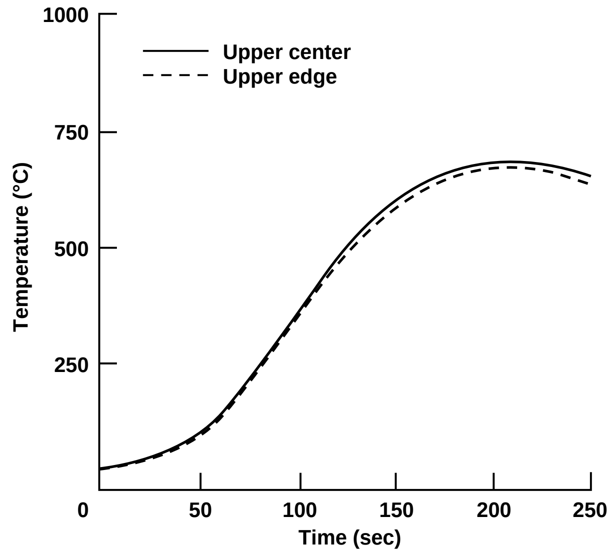

Figure 15. Calculated temperature history of recommended cooled window design during the AFE aeropass. The maximum temperature reached is well below 800°C. This window would be capable of providing reliable 174-nm data over the entire aeropass.

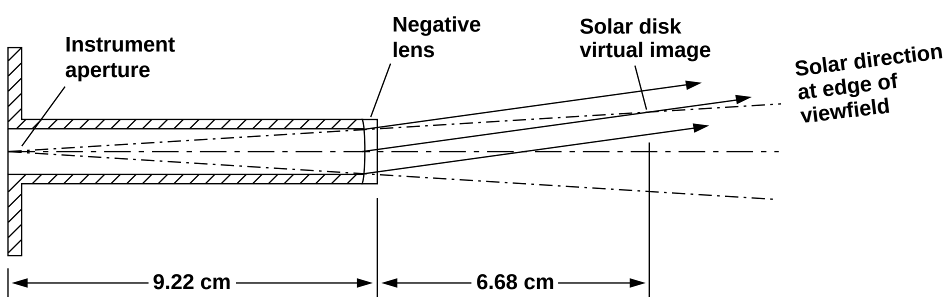

Figure 16. Sketch of a lens-apertured window based on AFE dimensional requirements. The larger viewfield requirement for the solar calibrations is accommodated by shaping the inner surface of the window into a negative lens. A virtual image of the solar disk is formed within the field of view of the instrument aperture.

requirements for the AFE, is shown in figure 16. A virtual image of the solar disk is formed within the extended field of view of the internal solid angle. The negative curvature, only 0.2 mm concave at the center in the present case, would have negligible effects on performance during the arc-jet tests. Use of data gathered under this configuration would, of course, require specification of the slightly different geometrical interpretation of the radiating regions of the shock layer contributing to the signal.

Window Contamination

Window contamination is a serious concern with respect to data credibility. Trace window contaminants can significantly increase the uncertainty of radiometric data, particularly in the UV. Sensor windows can be fouled during all phases of the AFE mission by contaminants from a variety of sources. Any spacecraft experiment team expecting to gather reliable radiometric data will have to be particularly insistent on the presence and thoroughness of a project level contamination control activity to identify, assess, and control the problem. An estimate of the expected contamination, from an inventory of known contaminants, is important to help assess the validity of the solar calibrations and the data. Three types of window contamination, their sources, and implications for this kind of mission application are discussed below. A test program to characterize these effects was part of the window development plan and is described.

The importance of controlling contaminants requires that a high priority be given to this activity at every phase of the experiment, spacecraft, and mission design.

Particulates (i.e., dust)– Sources include dust-laden air after the “last access” point when no further cleaning or inspection is permitted, launch vehicle (i.e., STS or other carrier) payload bay dust dislodged during launch, orbit operations in the vicinity of the launch vehicle, and particulates ejected by firing of a maneuvering RCS rocket from either the launch vehicle or the spacecraft.

Protective covers should protect the windows during most ground operations. After final cover removal and cleaning, a characterized clean room environment should be maintained. Vertically positioned radiometer windows will reduce agglomeration of particulates to about 5% of the horizontal rate in a 1-G environment. The mission activity is different: During the launch of the STS, for example, payload bay dust, including dust from companion payloads, is violently agitated and then it “settles” uniformly on all exposed surfaces.

The particulates from the RCS activities can be ameliorated simply by avoiding the spray pattern of the RCS engine. Monopropellant grade hydrazine can contain as much as 1 mg/liter of particulates, and a high purity grade is available if required.

The effect of contamination from these particulates should be fairly nonwavelength sensitive; an assessment would be possible from the solar calibrations.

Volatile contaminants (compounds of small molar mass, e.g., H_2O or NH_3)– These contaminants are threats to optical surfaces if they chemically attack the material or if they are deposited as aerosols containing dissolved solutes that are left behind after evaporation. Potential sources are migration from saturated surfaces and from venting and exhaust products of thruster motors. Airborne aerosols, particularly of NaCl in water, could be a problem, for example, at Kennedy Spacecraft Center because of its proximity to the ocean.

Nonvolatile contaminants (nonvolatiles of large molecular mass such as polymeric compounds, including silicone derivatives– This class of contaminant is the most deleterious to the radiometry experiments. They can be derived from a variety of sources. They are difficult to remove and in general are strong radiation absorbers, particularly of UV photons. Sources of these contaminants are the spacecraft itself, the payload bay, and companion payloads. Generation is primarily from polymeric compounds, i.e., plastics that are used as matrix binders, in circuit boards, films, adhesives, or coatings. With respect to the AFE, silicones are worrisome in this regard because they are used extensively in the heat shield bonding and they will probably bond strongly to the window material. Solar heating of the spacecraft and the resulting increase of production of these contaminants in the vacuum before atmospheric entry pose a special situation to be assessed. The firing of a major rocket motor can also be a source of nonvolatile fouling as well as the thermal degradation of the polymeric insulation liner after shutdown. During the aeropass, contaminants generated from the heat shield by the atmospheric heating will be carried in the boundary layer flow and then possibly deposit on the windows. In order to quantify the sensitivity to this form of contaminant, an estimate was made of the allowable level of film thickness of nonvolatile contaminants. To limit beam attenuation to less than 1.5% at 200 nm, the maximum allowable film thickness is 0.5 nm assuming the reasonable value for the extinction coefficient of 0.0002 nm^{-1}. If we consider the probable molecular size of these compounds, this value undoubtedly represents a less than monomolecular layer.

Silicide coating contamination– As seen in figures 11 and 13, the designs of the arc-jet wind tunnel test specimens included a silicide coating on the metallic portions of the window mount that would be exposed to the flow. Spacecraft experience has shown that this coating is effective in eliminating the metal erosion from the boundary layer atomic oxygen during atmospheric entries. This coating could likely be part of the design of the flight windows, but more work is required to evaluate the effect on the scientific objectives of the experiment. Arc-jet wind tunnel tests have demonstrated that this material contains volatiles that will be introduced into the boundary layer during the entry (ref. 14). These volatiles can deposit on a nearby cool surface, such as a window, and then be reevaporated as the surface heats up. Removal of these volatiles, however, does not seem to affect the ability of the coating to provide the desired oxidation protection, so it is possible that sufficient preconditioning of a flight article would avoid these problems.

The use of a silicide coating needs to be assessed from the standpoint of introducing radiators or absorbers into the boundary layer above the window and from the standpoint of coating the window with an absorber. An initial assessment of the former consisted of several tests conducted to compare emission spectra from the radiating region near the window with and without a silicide coated holder. Material ejected from the silicide, entering the boundary layer, should show added spectral features. The setup is shown in figure 17. Spectra were taken from 450 to 850 nm and no differences were noted. Although encouraging, this test was not exhaustive enough to validate flight design performance.

The transient nature of any resulting condensate on the window, and the somewhat contaminated environment of the arc-jet free stream, makes post-test examination insufficient to evaluate the latter, namely whether the condensate would affect the science data. Both of these concerns could be assessed by straightforward further testing. Arc-jet wind tunnel tests could be performed to measure the time history of the shock layer radiation, especially in the UV, transmitted through a candidate sapphire window mounted with its coated holder. The results could then be compared with measurements made without the influence of the silicide coating. References 15 and 16 describe the latter results and the setup that could be used for this evaluation.

The present uncertainty of the usefulness of the silicide coating was a factor in the layout of the recommended design discussed earlier and shown in figure 14. The window holder is entirely enclosed in the heat shield material.

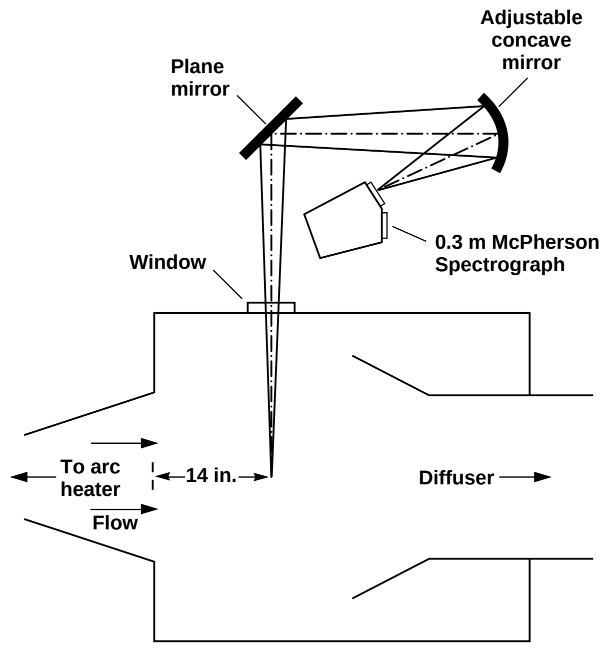

Figure 17. Sketch of setup to detect outgassing contamination from the silicide coating on the window mount. Arc-jet tests were conducted to simulate the aeropass heating. Spectra were measured from the region near the window with and without the silicide coated material in place. The spectra were from 450 to 850 nm and compared.

Contamination effects measurements– Contaminations deposited on the window before the entry could be detected and characterized by the solar calibrations, and their effects on the data could be quantified. But contamination could be of a transitory nature and it would change, or exist only during the aeropass. This kind of contamination is insidious in that its presence is impossible to directly quantify. Examples of this type would be a preexisting volatile coating vaporizing during the aeropass, optically absorbing gases from spacecraft volatiles in the boundary layer at the window location, and material deposited on the window surface early in the trajectory but vaporized later as the window temperature rises. It is necessary to establish upper limits of this class of contamination effect if the data are to be used with confidence. The RHE window development plan included a test to directly measure the effects of transitory contamination on the optical performance during a simulated entry, as follows:

The shock layer radiative flux incident on the surface of a water cooled blunt model placed in the supersonic stream of the ARC 20 MW Aerodynamic Heating Facility has been characterized (refs. 15 and 16) by measurements made from 120 to 900 nm. These measurements were made through a specially built optical apparatus with a cooled MgF_2 window at the stagnation region of the model. An evacuated optical system and a system of mirrors was used to transmit and couple the vacuum UV surface flux onto the entrance slit of a vacuum spectrograph. A new test model of the same diameter as this blunt model would be built to provide the test platform to assess the contamination problem of the flight article. This test model would match the flight article as closely as possible, with the materials and geometry of the spacecraft thermal protection system and with the flight window and its metallic mount in flight position. Time varying measurements of the shock layer radiation would be repeated through the flight window with this model in place of the cooled model during an imposed heating rate to simulate the aeropass heating rates and heat shield and window temperatures. Comparison of the data with the same measurements using the cooled model would quantify any development of contamination on the flight article. In addition, the model could be "seeded" with materials of possible concern to determine upper limits of problems.

A test series based on these conditions could identify objectionable materials to recommend avoidance by the spacecraft designers and could establish upper limits of other contamination effects.

V. Conclusions

Experiment objectives for the RHE of the AFE have been described. Although the project was canceled, the design of the experiment was well matured. The instruments, with the exception of the windowed aperture, had successfully completed a CDR. The experiment goal was to develop a data base characterizing the radiation flux incident on the forebody surface of an aerobrake returning from GEO. The purpose of the data base was to refine and validate aerothermodynamic computational models for these vehicles. Based on this goal, the experiment objective was to obtain stagnation region surface flux with 0.6 nm spectral resolution from 174 to 900 nm during the aeropass. There are serious questions about the importance of the VUV radiation from atomic lines. To help answer this concern, data from the atomic nitrogen at 174 nm is shown to be required from entry until about 100 sec into the trajectory and from about 200 sec on. Instrument performance specifications were generated from these requirements and a small grating spectrograph using a UV sensitive linear array was found to meet the specifications. Special, windowless arrays were found to be useful at 174 nm.

Although the window had not reached the maturity of the instruments, considerable progress had been made. The entry environment of high heating and exposure to the shock layer plasma present special problems; sapphire was chosen as the material. Window temperatures needed to be below 800°C for use at 174 nm. Small sapphire windows, both cooled and uncooled, were built. The former were conductivity cooled through a copper screen or washer brazed to the sapphire. The latter were insulated by ceramic material from the heat sink. Both of these kinds of windows successfully withstood overly conservative arc-jet wind tunnel testing. Scientific performance predictions of these windows were made using theoretical models of the radiant flux during the entry and window thermal performance models based on instrumented arc-jet tested specimens. Three designs are described that would partially or totally meet experiment objectives and would form the basis for the design of a flight window. A recommended design was described.

The importance of credibility of the data is discussed in the context of absolute calibrations and window contamination. Solar calibrations were designed as part of the mission scenario. The influence of these calibrations on window requirements is discussed and the use of a lens instead of a flat window is shown to be possibly required. Window contamination is important and requires special consideration by the experiment and mission designers.

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13. ABSTRACT ***(Maximum 200 words)***

This paper describes the techniques developed for measuring stagnation-point radiation in NASA's canceled Aeroassist Flight Experiment (AFE). It specifies the need for such a measurement, the types and requirements for the needed instruments, the Radiative Heating Experiment (RHE) developed for the AFE, the requirements, design parameters, and performance of the window developed for the RHE, the procedures and summary of the technique, and results of the arc-jet wind tunnel experiment conducted to demonstrate the overall concept. Subjects emphasized are the commercial implications of the knowledge to be gained by this experiment in connection with the Aeroassisted Space Transfer Vehicle (ASTV), the nonequilibrium nature of the radiationm, concerns over the contribution of vacuum-ultraviolet radiation to the overall radiationm, and the limit on the flight environment of the vehicle imposed by the limitations on the window material. Results show that a technique exists with which the stagnation-point radiation can be measured in flight in an environment of interest to commerical ASTV applications.

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